Fact sheet for "Human and natural influences on the changing thermal structure of the atmosphere"

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Summary: **Observational satellite data and the computer model response to human influence have a common pattern of changes in the thermal structure of the atmosphere. The key features of this pattern are global-scale tropospheric warming and stratospheric cooling over the 34-year satellite temperature record. We show that current climate models are highly unlikely to produce this distinctive signal pattern by internal variability alone, or in response to naturally forced changes in solar output and volcanic aerosol loadings. We detect a "human influence" signal in all cases, even if we test against natural variability estimates with much larger fluctuations in solar and volcanic influences than those we have observed since 1979. Our results highlight the very unusual nature of observed changes in atmospheric temperature.**

Signal-to-noise analysis: A brief primer

Our *PNAS* paper describes results from a climate change detection and attribution study, in which we investigate the causes of temperature changes in Earth's atmosphere. The focus of our study is on the vertical structure of atmospheric temperature change – in other words, on patterns of change that vary with latitude and with altitude. These patterns provide information about temperature changes in the troposphere and the stratosphere (see below):
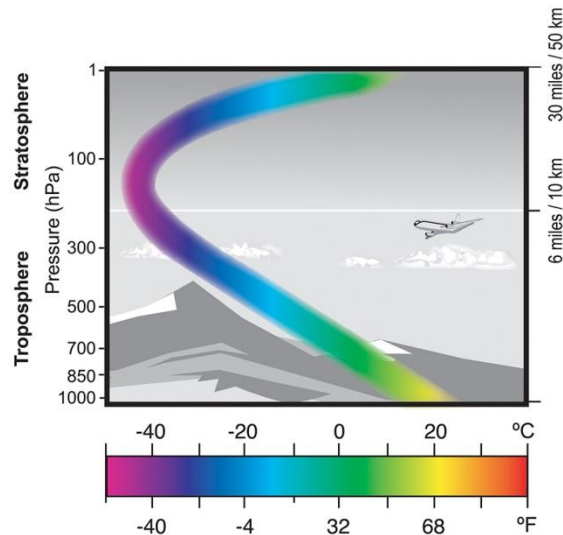

Figure 1: This Figure is from Synthesis and Assessment Product 1.1 of the U.S. Climate Change Science Program (*Karl et al.*, 2006[1]). It shows the approximate pressure and altitude boundaries of the troposphere and the stratosphere. The multi-colored line indicates the average dependence of temperature on altitude.

We rely on estimates of atmospheric temperature change from satellites and from computer models of the climate system ("climate models"). The satellite observations are made available by two different research groups; the simulation output is from as many as 20 of the models participating in phase 5 of the Coupled Model Intercomparison Project (CMIP-5).

In the real world, many factors – both human and natural – are simultaneously acting on the climate system. We do not have a "control Earth", on which there are no human-caused changes in atmospheric levels of greenhouse gases.

With climate models, however, it is possible to perform such controlled simulations. For example, we run climate models with our best estimates of the purely natural changes in volcanic activity and the

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[1]Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (*eds.*), 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 164 pp.

Sun's energy output over the last 1,000 years[2]. We can then ask whether these computer model estimates of the "world without us" produce climate-change patterns similar to the ones we have actually observed since 1979[3]. The availability of "world without us" results allows us to examine – and to test – persistent claims that observed changes in climate are primarily due to natural causes, like an increase in solar irradiance, or the "recovery" of atmospheric temperature after large volcanic eruptions.

Our paper also considers simulations in which only human influences act on the climate system, and there are no changes in solar or volcanic influences. Examples of human influences include changes in atmospheric levels of greenhouse gases and particulate pollution. Such "human effects only" simulations are used to estimate the climate-change signal (also called the "fingerprint") that we expect to see as a result of human activities[4].

Finally, the model simulation output gives us estimates of the year-to-year and decade-to-decade "noise" of internal climate variability, arising from such natural phenomena as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). This internal variability (which we refer to as V_{INT}) is unrelated to changes in the Sun, or to changes in volcanic activity.

We use a standard fingerprint method[5] to search for the model "human effects only" signal pattern[6] in the satellite observations. First, we quantify the changing strength of the signal pattern in observations. We then estimate the changes in signal strength that are caused by purely natural changes in climate.

Our signal detection method allows us to calculate so-called signal-to-noise (S/N) ratios. If the observed patterns of atmospheric temperature change are becoming increasingly similar to the model "human influence" fingerprint, and if the natural variability patterns are dissimilar to the fingerprint pattern, the S/N ratios will be large. S/N ratios larger than 3 show that there is highly significant correspondence between the model fingerprint and satellite data, and that natural climate variability is unlikely to explain this pattern match.

Our S/N ratios depend on the length of the temperature record. We focus on S/N ratios calculated over the full, 34-year period of the satellite data (1979 to 2012). Looking at long, multi-decade periods of record helps to reduce the impact of large, year-to-year natural variability, and more clearly reveals any underlying signal of human influences on climate.

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[2] Such simulations lack any human-caused changes in greenhouse gases or particulate pollution.
[3] The period over which we have been monitoring atmospheric temperature from space.
[4] Like the burning of fossil fuels.
[5] Our fingerprint method has been successfully employed for the identification of human effects on surface and atmospheric temperature, upper ocean heat content, the height of the tropopause (the boundary between the troposphere and stratosphere), and atmospheric moisture over oceans.
[6] As noted above, the signal is the latitude/altitude pattern of atmospheric temperature change.

Question 1: What's new about this research?

Two aspects are novel.

First, virtually all detection and attribution studies to date use computer model estimates of V_{INT} (natural internal variability; see definition in the "primer") to determine whether a human-caused climate change signal can be detected in observations. Here, we look at the signal detection issue in several different ways. We try to detect a human influence signal not only against the background noise of internal climate variability, but also against the natural variability information from the CMIP-5 "world without us" simulations. These simulations[7] give us estimates of the "total" natural variability of the climate system, V_{TOT}, which arises from the combined effects of internal variability, fluctuations in the Sun's energy output, and changes in the levels of volcanic particulates in the atmosphere.

Second, most previous detection and attribution studies with temperature changes in a "slice" through the atmosphere[8] used results from only one or two climate models, and from a single observational temperature data set. We consider results from up to 20 climate models, and from two different observational data sets[9]. This enables us to determine whether previous claims of the positive detection of a human fingerprint in satellite temperature records are sensitive to current uncertainties in models and observations. We find that prior "positive detection" claims[10] are robust to the model and observational uncertainties considered here.

Question 2: What are your key findings?

In the satellite data, we've observed a pattern of large-scale warming of the lower atmosphere (the troposphere) and cooling of the stratosphere. Computer model estimates of the "human influence" fingerprint are broadly similar to the observed pattern (see Fig. 2). In sharp contrast, model simulations of internal and total natural variability cannot produce the same sustained, large-scale warming of the troposphere and cooling of the stratosphere. So in current climate models, natural causes alone are extremely unlikely to explain the observed changes in the thermal structure of the atmosphere.

This is true even if our signal detection approach uses total natural variability estimates from before the period of satellite temperature observations[11]. The "world without us" simulations sample changes in

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[7]Which are referred to as "NAT" and "P1000" in our paper.

[8]In other words, at the pattern of temperature change with latitude and altitude.

[9]One of the two observational groups (Remote Sensing Systems in Santa Rosa) explored uncertainties in the processing steps used to create the observations, and developed a set of four hundred plausible estimates of observed atmospheric temperature change. We used this "ensemble of observations" in our detection study.

[10]See, *e.g.*, Santer, B.D., K.E. Taylor, T.M.L. Wigley, T.C. Johns, P.D. Jones, D.J. Karoly, J.F.B. Mitchell, A.H. Oort, J.E. Penner, V. Ramaswamy, M.D. Schwarzkopf, R.J. Stouffer, and S. Tett, 1996: A search for human influences on the thermal structure of the atmosphere. *Nature*, **382**, 39-46.

[11]The last 34 years.

volcanic and solar activity over the last 150 to 1,000 years. Many of these eruptions and solar irradiance changes are much larger[12] than the volcanic and solar changes we have observed since 1979. A remarkable aspect of our results is that even in this "worst case" signal detection situation, when we make signal identification difficult by using very large estimates of total natural variability, we still obtain consistent detection of a "human influence" fingerprint.

Satellite observations (Remote Sensing Systems)
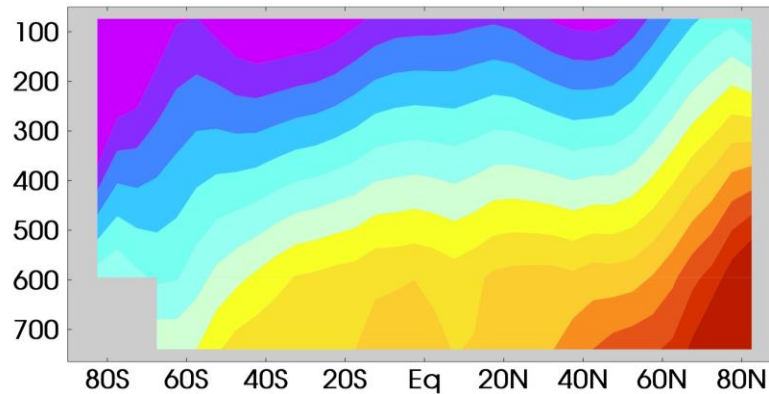
Climate models (average of "human influence" simulations)
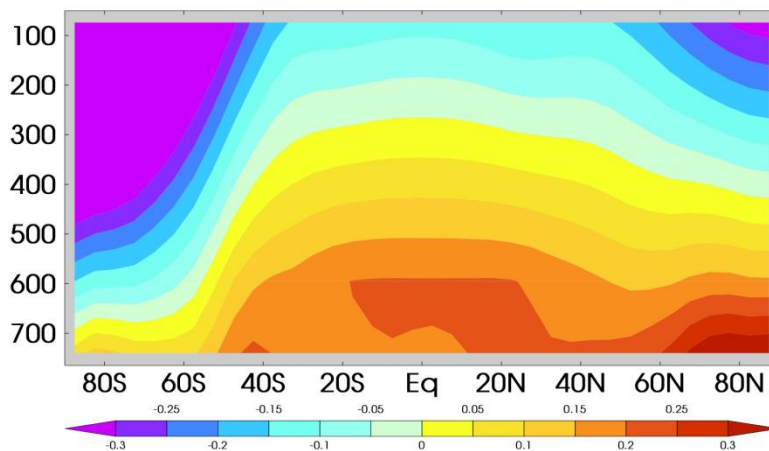

Figure 2: The vertical structure of changes in atmospheric temperature in satellite observations (top panel) and in computer model simulations performed as part of phase 5 of the Coupled Model Intercomparison Project (CMIP-5; bottom panel). As described in the *PNAS* paper, both panels provide a vertically smoothed picture of atmospheric temperature change. Information from only three atmospheric temperature layers – the lower stratosphere (TLS), the mid- to upper troposphere (TMT), and the lower troposphere (TLT) was used in generating the two plots. We show temperature changes in this "vertically smoothed" space because satellite-based estimates of atmospheric temperature change are available for TLS, TMT, and TLT, and because our signal detection study is performed with the zonally-averaged temperature changes for these three layers. All temperature changes are in the form of linear trends (in degrees Celsius) over the 408-month period from

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[12]Examples include the major eruptions of Krakatoa in 1883 and Kuwae in 1452, and the large estimated changes in solar irradiance around the time of the Maunder Minimum (from roughly 1645 to 1715).

January 1979 to December 2012. The model results are an average of "human influence" simulations performed with 8 different CMIP-5 models. The y-axis shows atmospheric pressure (in hectoPascals).

Question 3: Is there evidence that the models you've used here systematically underestimate the total natural variability of atmospheric temperature?

If the CMIP-5 models analyzed here systematically underestimated the size of observed "total" natural variability, our S/N ratios would be spuriously inflated. In our previous work[13], we found no evidence that this is the case. To test the fidelity with which models simulate observed total natural variability, we compared modeled and observed temperature fluctuations on decadal timescales.[14] On average, the CMIP-5 models substantially <u>overestimate</u> the size of observed tropospheric temperature variability, suggesting that our S/N ratios are probably too conservative[15].

Question 4: Are there remaining problems?

Yes. Although we found a "pattern match" between the modeled and observed vertical structure of atmospheric temperature changes, most models have problems capturing the size of the observed changes. On average, the CMIP-5 models underestimate the observed cooling of the lower stratosphere, and overestimate the warming of the troposphere[16]. Some scientists have claimed that there is only one possible interpretation of such differences – that models are too sensitive to greenhouse gas increases. Such claims are incorrect. There are multiple interpretations of differences between modeled and observed temperature changes. Other possible explanations include: A) residual errors in the observations; B) an unusual sequence of natural climate fluctuations in the observations; and C) the neglect or inaccurate specification of key "forcings" in model simulations of historical climate change. Results presented in our PNAS paper and elsewhere suggest that forcing errors make an important contribution to the biases in model temperature trends[17].

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[13]Santer, B.D., J.F. Painter, C.A. Mears, C. Doutriaux, P. Caldwell, J.M. Arblaster, P.J. Cameron-Smith, N.P. Gillett, P.J. Gleckler, J. Lanzante, J. Perlwitz, S. Solomon, P.A. Stott, K.E. Taylor, L. Terray, P.W. Thorne, M.F. Wehner, F.J. Wentz, T.M.L. Wigley, L.J. Wilcox, and C.-Z. Zou, 2013: Identifying human influences on atmospheric temperature. *Proceedings of the National Academy of Sciences*, **110**, 26-33, doi: 10.1073/pnas.1210514109.

[14]This analysis used digitally-filtered temperature data; the filtering highlighted temperature variability on timescales ranging from 5 to 20 years.

[15]In the lower stratosphere, the size of modeled and observed decadal variability is (on average) very similar.

[16]Particularly in tropics and Southern Hemisphere (see Fig. 2).

[17]Note that these biases have relatively small impact on the S/N results presented here. This is because the searched-for fingerprint patterns are normalized – thus reducing the effect of biases in the size of modeled temperature changes.